APPENDIX C

Hydraulic Aperture Determinations From Borehole Information In the Chatsworth Formation at the Santa Susana Field Laboratory (SSFL)

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Introduction

Fractures play an important role in determining flowpaths in groundwater flow systems and have major influences on contaminant migration. The size of the opening in the rock, called the fracture aperture (2b), controls how much fluid can flow though the fracture. Prior to the 1980's, a rock fracture was considered to have characteristics similar to a pair of parallel plates separated by a constant distance, thus having a constant aperture as shown in Figure 1(a). Hydraulically, these aperture widths are characterized using the cubic law, which is derived from the Navier-Stokes equation for the flow of an incompressible fluid between two uniformly parallel plates (Snow, 1969). The solution of the Navier-Stokes equation is known as plane Poiseuille. The cubic law is expressed as:

$$Q/\Delta H = C(2b)^3 \qquad (1)$$

Where Q = flow rate (V/T)

ΔH = unit head (L/L)

C = constant (fluid properties and flow dimensions)

2b = fracture aperture width (L)

In a large hydraulic system, fractures are random in both location and orientation. The number of fractures per unit distance across a rock face (N) and their respective aperture values (2b) combine to form the parameter fracture porosity (ϕ_f), expressed as:

$$\phi_f = N(2b) \qquad (2)$$

Snow (1968) related the fracture porosity and the hydraulic conductivity (K) of jointed rocks to the joint geometry with the equation:

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$$K = \{(\rho g)/\mu\} * \{[N(2b)^3]/12\} \quad (3)$$

Where: ρ = density of water

g = gravitational constant

μ = kinematic viscosity of water

by assuming all fractures had an equal aperture and that they were distributed as a parallel array of planar joints. Hydraulic conductivity is related to transmissivity by the saturated thickness of the interval being tested, expressed as:

$$T=Kb \quad (4)$$

Where: T = transmissivity

b = saturated thickness of test interval

Further inspection of fracture properties lead to the realization that fractures have rough walls and therefore consist of an aperture value that varies over its length as shown in Figure 1(b). Variations in fracture properties such as fracture aperture and fracture spacing have a direct influence on the flow rates and direction of fluid flow in these fractures. Neuzil and Tracy (1981) formed a model for flow in a fracture that was considered to be a set of parallel plate openings, generally with different apertures. The model developed a modified Poiseuille equation for flow which includes an aperture frequency distribution for the fracture.

Fracture apertures are commonly determined by two methods: tracer tests and hydraulic tests. Apertures derived from tracer tests involve the measurement of the mean residence time of tracer transport as well as some other parameters such as volumetric flow rate or the hydraulic head difference, depending on which method is chosen (Tsang, 1992). Hydraulic apertures are derived using hydraulic field

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measurements of volumetric flow and pressure drop. No tracer transport measurements are involved with this type of aperture calculation. The hydraulic aperture relates to the transmissivity of the fracture and is probably the most widely used aperture in the literature.

This report provides calculations and interpretations of hydraulic aperture values obtained from borehole information at the Santa Susana Field Laboratory (SSFL). A brief description of the different field testing techniques and subsequent data analysis methods are covered in the following sections.

Field Techniques

Hydraulic parameters can be determined by a variety of field tests using either a single borehole or by altering the pressure in one borehole and monitoring the pressure responses in surrounding monitoring wells. Several different data sets exist from different field techniques that have been employed over the past decade at SSFL. Descriptions of these techniques are discussed separately in the following sections and include: 1) pumping tests; 2) straddle packer injection tests; 3) single packer tests; 4) multilevel system low-flow double packer tests.

Pumping Tests

Pumping tests are typically performed by withdrawing water at a constant rate from one well and observing the water level change over time in the pumping well and in the nearby observation wells. The temporal variation in the water levels depends primarily on the rate at which water is pumped, the geometries of the well and the aquifer and the aquifer permeability. As water is being pumped, the water

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levels will decrease, thus the data set is called “drawdown data”. When pumping is ceased, the water levels will rise and eventually return to their natural level. This data set is called “recovery data”. These data sets are then analysed by using a model which is best suited for the conditions of the aquifer in question and a value of transmissivity and hydraulic conductivity is calculated.

Straddle Packer Testing

Straddle packer testing involves the use of two pneumatically inflatable rubber packers that are seated against the borehole wall in order to isolate a selected test interval. Water is injected into this isolated interval at a constant pressure and the variation of injected flow rate versus time is recorded. Once the flow rate becomes constant, steady-state conditions are achieved. The length of time required to reach steady state conditions is a function of the formation permeability. Pressure transducers monitor the change in pressure below, within, and above the test interval. The hydraulic conductivity is calculated from the flow rate, length and radius of the test interval in the borehole, and the effective head within the packer-isolated interval.

When a constant flow rate cannot be achieved, an alternative packer test can be performed by shutting the pressure in the test section and monitoring the pressure decay within the isolated interval. This type of test is called a pressure decay test. Transmissivity values are calculated from the relationship between the pressure decay and the elapsed decay time.

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Single Packer Testing

Single packer testing involves a single inflatable packer that seals against the borehole wall and isolates the bottom section of the borehole. Water is pumped from the test interval at a constant rate and the water level in the borehole above the packer was monitored manually, while the pressure within the isolated interval is monitored with a vibrating wire transducer. Both drawdown and recovery data is collected and analysed similar to the traditional pumping tests mentioned above.

Multilevel System Low-Flow Double Packer Tests

Removable multilevel systems were installed in both RD-35B and RD-46B for the duration of 1998 as part of a broader study conducted by the University of Waterloo (Sterling, 1999). These systems were manufactured by a groundwater instrumentation company, Solinst Canada Limited, based in Georgetown, Ontario, Canada. The monitoring systems were constructed with six discrete intervals that were separated by inflatable rubber packers. Each sample interval was equipped with a double valve pump and a vibrating wire pressure transducer. Water is pumped from one monitoring interval while changes in hydraulic pressure are recorded by the vibrating wire transducers. The cyclic pressure and vent pattern of the double valve pumps make it difficult to use any drawdown data when calculating transmissivity and hydraulic conductivity values from pumping test results. As a result, only recovery data were used.

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Fracture Frequency

Regardless of which testing method is used, information on fracture occurrence is needed to calculate fracture aperture from transmissivity as shown in equation (3). In these calculations, several assumptions were made. The first is that all fractures within a test interval are equally contributing to the allowable flow when measuring transmissivity. The number of fractures within a test interval was determined after studying all borehole logs produced prior to the hydraulic test. In the event that no geologic data were available for a test interval, only one fracture was assumed to be contributing to the flow, thus giving the worst case scenario.

BOREHOLES RD-35 AND RD-46 DATA ANALYSIS AND RESULTS

The fracture distribution of two borehole locations at SSFL (RD-35 and RD-46) were studied intensively by Sterling (1999) and multiple hydraulic tests were performed. Table 1 summarizes the vertical sections of boreholes that were hydraulically tested in RD-35A&B and RD-46A&B respectively and the resulting fracture aperture calculations. A combination of pumping tests, single packer tests, low flow double packer tests with a multilevel system and straddle packer tests were performed. Depending on the test method, various analytical methods were used to calculate transmissivity values for each test section.

One of two analytical methods was used for all packer testing results depending on the rock formation conditions. The first method, called the constant head test, was attempted on all of the test intervals and is called the constant head test. This is a standard procedure (# USBR 7310-89) that is outlined in detail in the

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United States Bureau of Reclamation (USBR) Earth Manual (1974). When the hydraulic test was performed in a very low permeability formation, it was not possible to conduct a constant head test, thus a pressure decay test or "shut-in" test was conducted. Bredehoeft and Papadopulos (1980) introduce this testing and analysis procedure in detail. Only one test section required analysis using the shut-in, pressure decay test procedures. For all of the remaining hydraulic testing data sets transmissivity values were calculated using the Theis & Jacob curve matching technique and formulaes, which requires recovery data. An analytical program called, "Aquifer Test V 2.01" was used for these calculations.

Fracture aperture values were calculated for all of these testing techniques using equation (3) as outlined above. Fracture summary data were determined from multiple borehole geophysical tests conducted by the United States Geologic Survey (USGS) during December, 1998. These tests included acoustic televiewer log, caliper log, borehole image processing log (BIPS), and flowmeter logs. In the event that data was not available from the USGS report, the number of fractures in a given test interval was estimated from core logs collected by GWRC at the time of drilling. Table 1 summarizes these results and shows the calculated fracture apertures ranging from 10 to 299 μm, with a simple arithmetic mean of 106 μm and a geometric mean of 70 μm. The distribution of these fracture aperture values are summarized in a histogram and shown in Figure 2.

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TABLE 1. Summary for Hydraulic Testing Analysis for boreholes RD-35B and RD-46B.

Test Interval (feet)	Test Method	Analysis Method	T, (cm^2/s)	K, (cm/s)	# fractures[1]	2b, (μm)
RD-35 BOREHOLE LOCATION						
30 - 110 ft (RD-35A)	Pumping Test (GWRC)	Theis & Jacob Curve Matching (Aquitest)	3.79E-02	1.38E-04	3*	116
30 - 110 ft (RD-35A)	Response to RD-35B Packer Test (GWRC)	Theis & Jacob Curve Matching (Aquitest)	5.33E-01	9.85E-04	3*	279
122.6 - 162 ft (RD-35B Upper Section)	Packer Test (GWRC)	Theis & Jacob Curve Matching (Aquitest)	7.00E-01	5.83E-04	6*	243
189.5 - 208 ft (RD-35B, Zone 6)	Multilevel Low Flow Packer Test (UW)	Theis & Jacob Curve Matching (Aquitest)	2.34E-01	4.15E-04	6	168
189.5 TO 210.1 FEET (RD-35B, Zone 6)	Straddle Packer Test (Connor Pacific/EFW)	Constant Head	2.29E-01	3.65E-04	6	167
225 TO 245.6 FEET (RD-35B, Zone 5)	Straddle Packer Test (Connor Pacific/EFW)	Constant Head	2.10E-03	3.35E-06	6	35
227 - 241.5 ft (RD-35B, Zone 5)	Multilevel Low Flow Packer Test (UW)	Theis & Jacob Curve Matching (Aquitest)	4.01E-04	9.00E-07	6	20
245 TO 265.6 FEET (RD-35B, Zone 4)	Straddle Packer Test (Connor Pacific/EFW)	Constant Head	8.16E-04	1.30E-06	7	24
249.5 - 262 ft (RD-35B, Zone 4)	Multilevel Low Flow Packer Test (UW)	Theis & Jacob Curve Matching (Aquitest)	5.47E-05	1.43E-07	7	10
292 - 328 ft (RD-35B Completed Well)	Pumping Test (GWRC)	Theis & Jacob Curve Matching (Aquitest)	2.76E-03	2.10E-06	10	32
303 - 321.5 ft (RD-35B, Zone 3)	Multilevel Low Flow Packer Test (UW)	Theis & Jacob Curve Matching (Aquitest)	6.21E-02	1.10E-04	2	156
303 TO 323.6 FEET (RD-35B, Zone 3)	Straddle Packer Test (Connor Pacific/EFW)	Constant Head	2.22E-02	3.53E-05	5	81
310 TO 315 FEET (RD-35B, Zone 3)	Straddle Packer Test (Connor Pacific/EFW)	Constant Head	6.10E-03	4.00E-05	2	72
334.5 - 339 ft (RD-35B, Zone 2)	Multilevel Low Flow Packer Test (UW)	Theis & Jacob Curve Matching (Aquitest)	1.70E-04	1.24E-06	1	28
346 - 350.5 ft (RD-35B, Zone 1)	Multilevel Low Flow Packer Test (UW)	Theis & Jacob Curve Matching (Aquitest)	1.75E-04	1.28E-06	1	28
346 TO 351 FEET (RD-35B, Zone 1)	Straddle Packer Test (Connor Pacific/EFW)	Constant Head	4.11E-04	2.70E-06	1	37
351 TO 356 FEET (RD-35B, Below Zone 1)	Straddle Packer Test (Connor Pacific/EFW)	Pressure Decay	8.84E-06	5.80E-08	1	10
RD-46 BOREHOLE LOCATION						
30 - 140 ft (RD-46A)	Pumping Test (GWRC)	Theis & Jacob Curve Matching (Aquitest)	2.63E-01	1.44E-04	5	186
153.4 - 190.5 ft (RD-46B Upper Section)	Packer Test (GWRC)	Theis & Jacob Curve Matching (Aquitest)	1.75E+00	1.55E-03	8*	299
240 TO 260.5 FEET (RD-46B, Zone 6)	Straddle Packer Test (Connor Pacific/EFW)	Constant Head	1.78E-03	2.85E-06	2	48
241 - 260.5 ft (RD-46B, Zone 6)	Multilevel Low Flow Packer Test (UW)	Theis & Jacob Curve Matching (Aquitest)	1.18E-04	1.99E-07	2	19
275 TO 295.5 FEET (RD-46B, Zone 5)	Straddle Packer Test (Connor Pacific/EFW)	Constant Head	1.77E-01	2.83E-04	6	152
276.5 - 294 ft (RD-46B, Zone 5)	Multilevel Low Flow Packer Test (UW)	Theis & Jacob Curve Matching (Aquitest)	1.63E-01	8.50E-03	6	149
281 - 328 ft (RD-46B - Completed Well)	Pumping Test (GWRC)	Theis & Jacob Curve Matching (Aquitest)	2.63E-01	3.43E-05	25	109
299 TO 303.9 FEET (RD-46B, Zone 4)	Straddle Packer Test (Connor Pacific/EFW)	Constant Head	8.96E-02	6.00E-04	1	222
301 - 303.5 ft (RD-46B, Zone 4)	Multilevel Low Flow Packer Test (UW)	Theis & Jacob Curve Matching (Aquitest)	2.90E-02	3.80E-04	1	153
304 TO 324.5 FEET (RD-46B, Zone 3)	Straddle Packer Test (Connor Pacific/EFW)	Constant Head	3.19E-02	5.10E-04	9	163
306.5 - 323 ft (RD-46B, Zone 3)	Multilevel Low Flow Packer Test (UW)	Theis & Jacob Curve Matching (Aquitest)	8.25E-03	1.64E-05	9	48
330 - 338.5 ft (RD-46B, Zone 2)	Multilevel Low Flow Packer Test (UW)	Theis & Jacob Curve Matching (Aquitest)	1.66E-04	6.39E-07	4	17
330 TO 341 FEET (RD-46B, Zone 2)	Straddle Packer Test (Connor Pacific/EFW)	Constant Head	2.96E-03	9.60E-06	4	44
352 TO 362.5 FEET (RD-46B, Zone 1)	Straddle Packer Test (Connor Pacific/EFW)	Constant Head	2.64E-03	8.25E-06	1	169
354.5 - 361 ft (RD-46B, Zone 1)	Multilevel Low Flow Packer Test (UW)	Theis & Jacob Curve Matching (Aquitest)	8.01E-03	4.04E-05	1	99

STATISTICS

MINIMUM	8.84E-06	5.80E-08		10
MAXIMUM	1.75E+00	8.50E-03		299
ARITHMETIC MEAN	1.44E-01	4.61E-04		106
MEDIAN	2.22E-02	3.53E-05		81
GEOMETRIC MEAN	8.40E-03	2.26E-05		70

Notes:

[1] number of fractures estimated from USGS borehole geophysical field summary 1998

* number of fractures estimated from GWRC borehole logs

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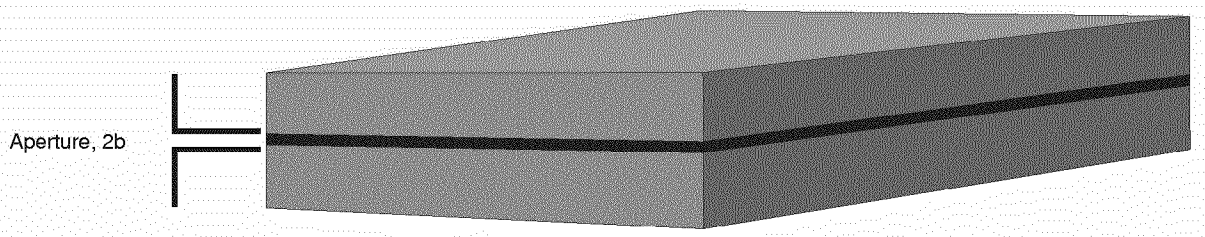

Figure 1(a). Schematic representation of a smooth walled fracture with aperture 2b. This parallel plate model is typically the geometry that fractures were first assumed to have, and thus have become the standard geometry for aperture calculations.

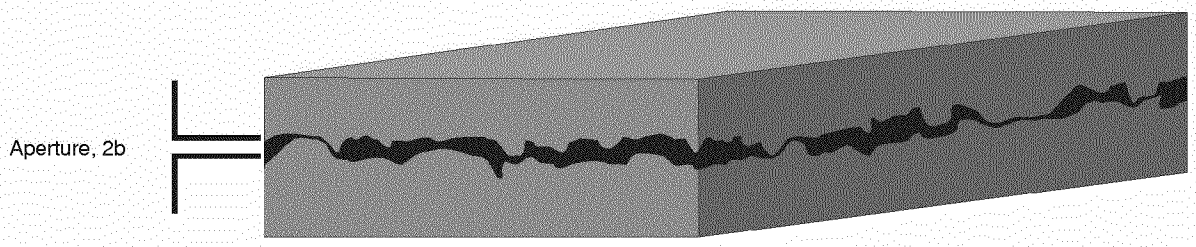

Figure 1(b). Schematic representation of a rough walled fracture with aperture 2b. This is the real geometry of a fracture, although due to its complexity, it is not used in aperture calculations.

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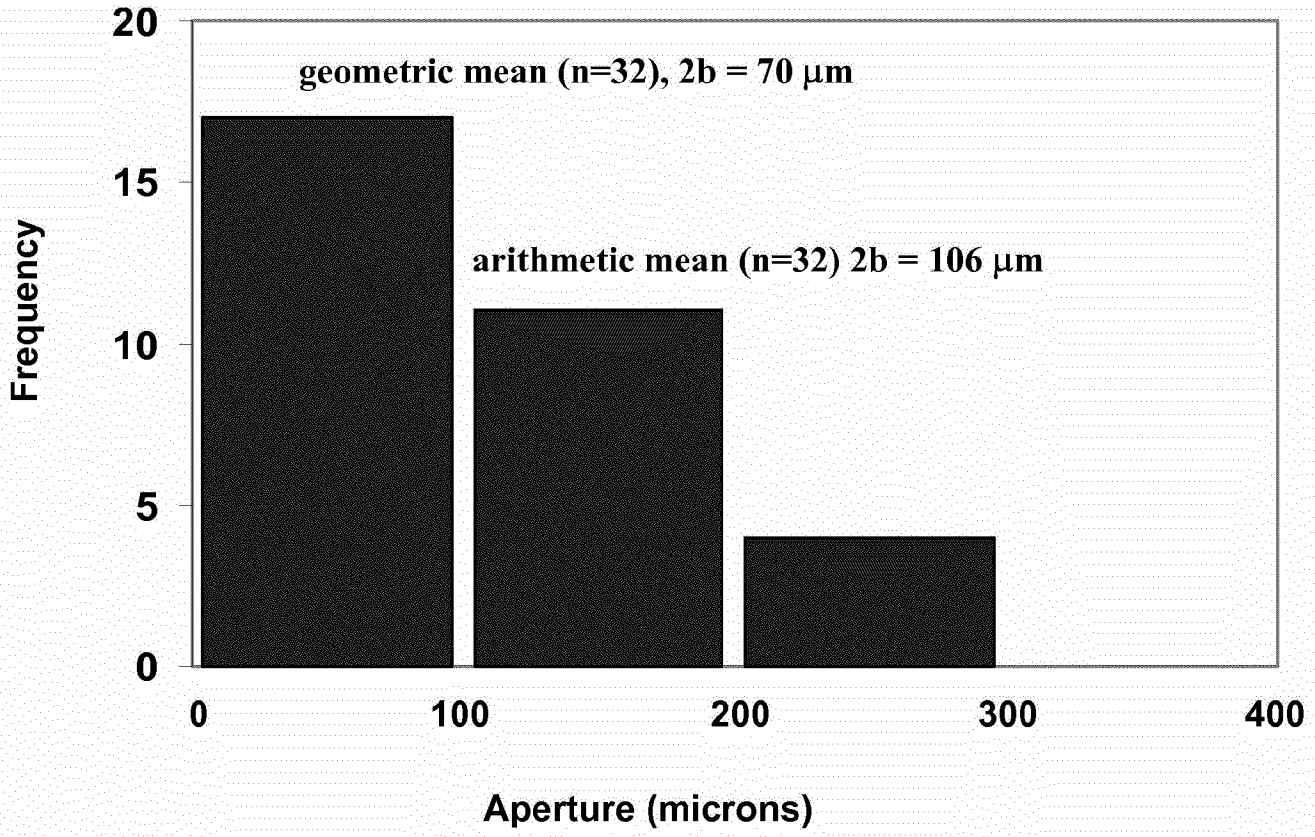

Figure 2. Summary of fracture hydraulic apertures calculated from 32 different isolated intervals in boreholes RD-35A, RD-35B, RD-46A and RD-46B boreholes at Santa Susana Field Laboratory (SSFL) during 1998.

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